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Characteristics of Fine Particulate Matter ($PM_{2.5}$) over Urban, Suburban, and Rural Areas of Hong Kong

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Abstract: In urban areas, fine particulate matter ($PM_{2.5}$) associated with local vehicle emissions can cause respiratory and cardiorespiratory disease and increased mortality rates, but less so in rural areas. However, Hong Kong may be a special case, since the whole territory often suffers from regional haze from nearby mainland China, as well as local sources. Therefore, to understand which areas of Hong Kong may be affected by damaging levels of fine particulates, $PM_{2.5}$ data were obtained from March 2005 to February 2009 for urban, suburban, and rural air quality monitoring stations; namely Central (city area, commercial area, and urban populated area), Tsuen Wan (city area, commercial area, urban populated, and residential area), Tung Chung (suburban and residential area), Yuen Long (urban and residential area), and Tap Mun (remote rural area). To evaluate the relative contributions of regional and local pollution sources, the study aimed to test the influence of weather conditions on $PM_{2.5}$ concentrations. Thus, meteorological parameters including temperature, relative humidity, wind speed, and wind directions were obtained from the Hong Kong Observatory. The results showed that Hong Kong's air quality is mainly affected by regional aerosol emissions, either transported from the land or ocean, as similar patterns of variations in $PM_{2.5}$ concentrations were observed over urban, suburban, and rural areas of Hong Kong. Only slightly higher $PM_{2.5}$ concentrations were observed over urban sites, such as Central, compared to suburban and rural sites, which could be attributed to local automobile emissions. Results showed that meteorological parameters have the potential to explain 80% of the variability in daily mean $PM_{2.5}$ concentrations—at Yuen Long, 77% at Tung Chung, 72% at Central, 71% at Tsuen Wan, and 67% at Tap Mun, during the spring to summer part of the year. The results provide not only a better understanding of the impact of regional long-distance transport of air pollutants on Hong Kong's air quality but also a reference for future regional-scale collaboration on air quality management.

Keywords: $PM_{2.5}$; meteorological variables; temporal evolution; urban and rural areas; Hong Kong

1. Introduction

Aerosols are particles suspended in the atmosphere with complex chemical composition and size that vary in both time and space and mainly exist within the atmospheric boundary layer. Fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) are atmospheric aerosol particles with aerodynamic diameters less than 2.5 μm and less than 10 μm, respectively, expressed in $\mu g \cdot m^{-3}$. These two aerosol groups have different sources and characteristics, but both interact with solar radiation and affect air quality, visibility, and the climate system [1]. They directly influence the Earth's energy budget, surface temperature, and precipitation, and degrade atmospheric visibility through light extinction. By changing the optical properties of clouds, they affect climate indirectly. Thus, they create uncertainty in the prediction of regional climate-effects, especially in the context of climate change [2–4].

$PM_{2.5}$ is emitted from natural and anthropogenic sources [5–7]. In urban areas, $PM_{2.5}$ is normally associated with local emissions from automobile exhausts [8]. This is not only the most important source of urban $PM_{2.5}$ [9,10] but also the main source of secondary particles in the atmosphere through chemical transformation (gas-to-particles) [11]. Studies indicate that tropical Asia contributes most to world air pollution due to the significant increase in aerosol pollutants from both anthropogenic and natural sources [12–16].

Ambient particulate matter (PM) causes severe health problems [17–19], but the health consequences depend on the size and composition of the particles, with $PM_{2.5}$ being the greater health hazard [20]. Studies have reported the association of PM with lung [21], respiratory [22], mutagenic [23], and cardiorespiratory diseases [24], and chronic effects such as asthma, and mortality, have been documented [25–27]. An increase of 10 $\mu g \cdot m^{-3}$ in $PM_{2.5}$ can increase, by 4%, 6%, and 8%, the rate of cardiopulmonary diseases, lung cancer, and mortality, respectively [28]. In Hong Kong, for every 10 $\mu g \cdot m^{-3}$ increase in the daily average concentration levels of PM2.5, there is approximately 2% more hospitalization and a 2% increase in the mortality due to respiratory diseases [29,30]. Children and elderly people are more vulnerable (Chau, et al. [31]).

In recent years, fine particulate pollution has become a global issue due to its impact on human health, air quality, and the climate system. Therefore, air quality monitoring stations have been established in many countries for regular measurement of $PM_{2.5}$, for epidemiological studies as well as for the management of air quality [32,33]. To understand the formation and dispersion of $PM_{2.5}$ in the atmosphere, studies have used ground-based surface meteorological variables, such as air temperature (TEMP), relative humidity (RH), precipitation (P), wind speed (WS), wind direction (WD), and mixing height (MH) [34–42]. Higher values of 24 h average $PM_{2.5}$ appear to be associated with lower temperatures [35,37,40] and its characteristics are shown to be affected by RH above 70% [43]. The concentrations of $PM_{2.5}$ appear to depend on TEMP, RH, MH, P, cloud cover, WS, and WD [35,37,42], but the association between $PM_{2.5}$ concentrations and meteorological variables varies with respect to region. Gupta et al. [44] reported correlation coefficients of −0.27 to −0.06, and −0.85 to −0.60 for $PM_{2.5}$ with TEMP and WS respectively, over Kolkata, India. Correlation coefficients of −0.58 and −0.33 were observed for $PM_{2.5}$ with TEMP and WS, respectively, over Fairbanks, Alaska [40].

In Hong Kong, only a few previous studies [45–48] are available on $PM_{2.5}$ and on the relationship between $PM_{2.5}$ and surface meteorological variables [49]. Shi et al. [49] found correlation coefficients of 0.50, −0.48, −0.37, −0.101, and 0.095 for daily average $PM_{2.5}$ against mean sea level pressure (MSLP), RH, TEMP, WD, and WS respectively, at the Central air quality monitoring station for the two years 2007 and 2008. Since their study covered only one urban air monitoring quality station, a detailed study of concentrations along with meteorological variables is still needed to understand the spatio-temporal behavior and characteristics of $PM_{2.5}$ over urban and rural areas of Hong Kong. In particular, since Hong Kong is often under the influence of regional haze, covering large parts of neighboring mainland China, the extent to which those living in suburban and rural areas of the territory are affected by $PM_{2.5}$ is unknown. Indeed, the source of poor air quality in Hong Kong has long been a controversial issue. The present study aims to investigate the characteristics of fine particulate matter ($PM_{2.5}$) with relevance to meteorological parameters over urban, suburban, and rural areas of Hong Kong, which could be a useful reference for the future regional-scale collaboration on air quality management. Therefore, the objective of this study is to analyze the spatio-temporal variations and characteristics of $PM_{2.5}$ using data from five air quality monitoring stations in urban, suburban, and rural areas of Hong Kong. For a better understanding of $PM_{2.5}$ variability with relevance to meteorological parameters, the influence of surface meteorological variables (TEMP, RH, WS, and WD) on $PM_{2.5}$ is examined.

2. Study Area and Data Sets

The Hong Kong Special Administrative Region (SAR) of China, with complex and hilly terrain, is situated on the southeast coast of China with an area of 1104 km^2. It is the world's densest city with a population density averaging 6540 people km^{-2} [50]. Hong Kong is facing severe air quality problems due to the presence of $PM_{2.5}$ in the atmosphere [51,52]. The air quality objectives (AQO) of Hong Kong are 35 $\mu g \cdot m^{-3}$ and 75 $\mu g \cdot m^{-3}$ for annual and 24 h $PM_{2.5}$, respectively [53] which are three times less stringent than the AQS (Air Quality Standard) of World Health Organization (WHO), which are 10 $\mu g \cdot m^{-3}$ and 25 $\mu g \cdot m^{-3}$ for annual and 24 h $PM_{2.5}$, respectively. Over the four years from 2005 to 2008 the annual mean $PM_{2.5}$ mass concentration of 40.35 $\mu g \cdot m^{-3}$ observed in the present study is slightly higher than Hong Kong's annual AQO (35 $\mu g \cdot m^{-3}$), but, four times higher than the WHO annual AQS (10 $\mu g \cdot m^{-3}$).

In this study, $PM_{2.5}$ data from March 2005 to February 2009 (hereafter 2005 to 2008) were obtained from the Environmental Protection Department (EPD) for five air quality monitoring stations located in Central (urban), Tsuen Wan (urban), Tung Chung (suburban), Yuen Long (urban) and Tap Mun (remote rural) (Figure 1, Table 1). The urban-suburban-rural areas are defined based on the building volume density (BVD) within the 1 km radius of the surrounding area (Table 1). $PM_{2.5}$ mass concentrations are measured under RH conditions between 40–50% using the Tapered–Element Oscillating Microbalance (TEOM) instrument with an accuracy of ±1.5 $\mu g \cdot m^{-3}$ for hourly averages. To check the influence of meteorological parameters on $PM_{2.5}$, ground-based hourly meteorological parameters such as TEMP, RH, WS, and WD are obtained from March 2007 to February 2009 (hereafter from 2007 to 2008) from the automatic weather stations (AWS; Table 1) installed by the Hong Kong Observatory (HKO). These AWS are installed at the HKO, located at distances of 2.8 km from Central, Tai Mo Shan (TMS), 5.2 km from Tsuen Wan, Sha Lo Wan (SLW), 4.1 km from Tung Chung, Wetland Park (WLP), 3.3 km from Yuen Long, and Tap Mun (TM), and 0.0 km from Tap Mun—air quality monitoring stations (Figure 1).

For the calculation, assume that A_{Pi} and h_i are the footprint area and height of building i of urban lot j (which has a total number of n buildings). Then, the total building volume of lot j is:

$$V = \sum_{i=1}^{n} A_{Pi} h_i$$

V_{max} is the highest V among all lots of the whole city. The building volume density of lot j is:

$$BVD_j = V_j / V_{max}$$

As a result, the calculated BVD is in a standardized numerical form that ranges from 0 to 1.

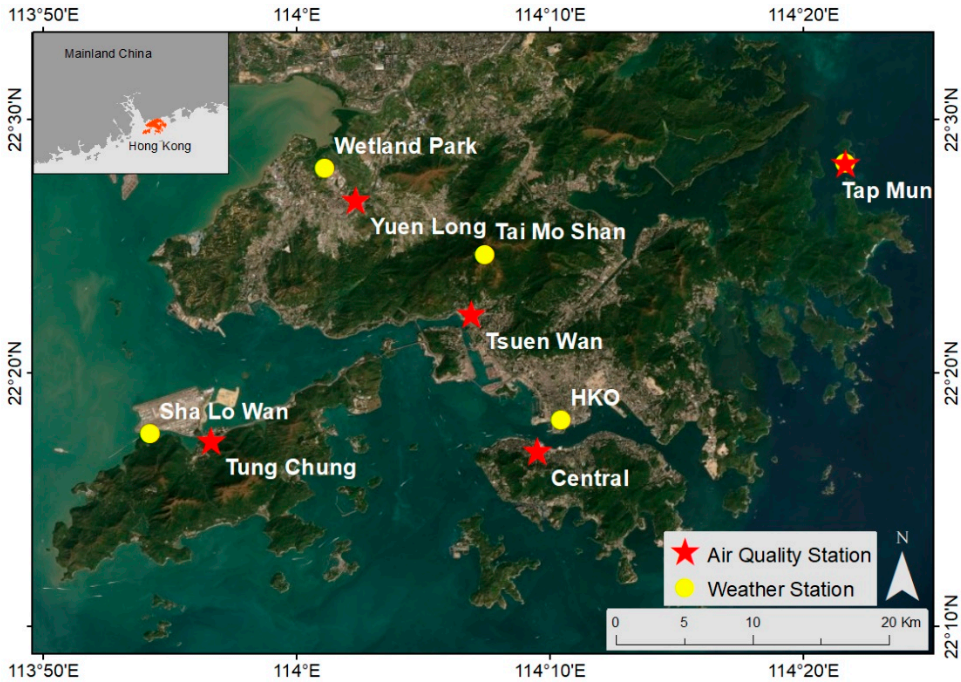

Figure 1. Study area and locations of ground-based air quality monitoring stations (stars) and the Hong Kong Observatory's climate stations (circles) in the hilly and complex terrain of Hong Kong.

Table 1. Description of air quality monitoring sites used in this study.

[1] AQMS	Description	Latitude (dd)	Longitude (dd)	[2] Elevation	[3] BVD
Central	city area, commercial area, and urban populated area	22.282	114.158	4.5	0.111
Tsuen Wan	city area, commercial area, urban populated, and residential area	22.372	114.115	17	0.088
Tung Chung	suburban and residential area	22.289	113.944	27.5	0.014
Yuen Long	urban and residential area	22.447	114.039	25	0.032
Tap Mun	remote rural area	22.471	114.361	11	0.000

[1] Air quality monitoring stations. [2] Evelation of the air quality monitoring stations above ground. [3] Building volume destiny (BVD) within 1 km radius. Note: BVD is a quantitative measure of building density in per unit area. BVD was used here to describe the selected sites because it has been used in the development of Hong Kong's urban climatic map (https://www.pland.gov.hk/pland_en/p_study/prog_s/ucmapweb/ucmap_project/content/reports/final_report.pdf).

3. Methodology

The methodology is based on the following steps:

1. The total number of exceedances were calculated; i.e., how many times $PM_{2.5}$ concentrations are greater than the AQO, using daily mean $PM_{2.5}$ concentrations from 2005 to 2008 for each air quality monitoring station.
2. Seasonal descriptive statistics for each station were calculated using the one-way ANOVA test based on the hourly $PM_{2.5}$ concentrations. To study the seasonal evolutions of $PM_{2.5}$, a year was classified into four distinct seasons: Winter (December–January–February: DJF), spring (March–April–May: MAM), summer (June–July–August: JJA), and autumn (September–October–November: SON) based on the prevailing significant meteorological changes observed in Hong Kong.
3. Temporal analyses based on daily and monthly mean data were performed to understand the temporal variations in $PM_{2.5}$ and exceedances with respect to the AQO of Hong Kong and AQS

of WHO. Furthermore, the four-year mean $PM_{2.5}$ concentrations were used to identify the most polluted (i) region, (ii) year, (iii) season, (iv) day, and (v) hour in Hong Kong.

4. Relationships between daily mean $PM_{2.5}$ concentrations and daily mean meteorological parameters (TEMP, RH, WS, and WD) were established using multiple linear regression, to understand the influence of meteorological parameters on $PM_{2.5}$ concentrations.

4. Results and Discussion

The daily mean $PM_{2.5}$ concentrations at the five air quality monitoring stations were analyzed for diurnal to seasonal variations, to depict the detailed spatio-temporal variability of air quality over the complex and rugged terrain of Hong Kong. Results show that the daily mean $PM_{2.5}$ concentration at all air quality monitoring stations is lower than HK's 24 h AQO (75 $\mu g \cdot m^{-3}$) in each season except for a very few values in winter at Tung Chung and Yuen Long (Table 2). From the viewpoint of local air quality guidelines, these results suggest good air quality conditions over urban, suburban, and rural areas of Hong Kong. However, the air quality condition at each station exceeds the WHO 24 h AQS (25 $\mu g \cdot m^{-3}$) on most days in spring, autumn, and winter, which is almost two to three times worse than the summer conditions.

Table 2. The total number of exceedances of daily mean fine particulate matter ($PM_{2.5}$) mass concentrations in different seasons from 2005 to 2008.

Air Quality Monitoring Station	AQO(HK)/AQS(WHO)	Number of Exceedances (HK/WHO)			
		Spring	Summer	Autumn	Winter
Central	75 $\mu g \cdot m^{-3}$/25 $\mu g \cdot m^{-3}$	0/92	0/77	2/90	2/92
Tung Chung		0/72	0/12	1/85	6/92
Tap Mun		0/74	0/13	0/85	1/91
Tsuen Wan		01/83	0/26	2/ 87	2/92
Yuen Long		0/79	0/21	2/88	5/92

Results for the one-way ANOVA test show that the four-year mean $PM_{2.5}$ concentrations during autumn and winter were significantly higher than those for spring and summer, which indicates consistently worse air quality conditions (Table 3). Air quality conditions were good during summer, as the four-year mean $PM_{2.5}$ concentrations were lower than Hong Kong's annual AQO (35 $\mu g \cdot m^{-3}$). Similar findings were reported by a previous study conducted over Hong Kong [49], which attributed the low concentrations of $PM_{2.5}$ in summer to fewer anthropogenic emissions than in winter, and also an increase in the atmospheric boundary layer height, allowing upward dispersal of pollutants. The findings are also consistent with another study in Hong Kong [45], which used microscale geographic predictors to estimate the fine-scale spatial variation of $PM_{2.5}$ concentration over Hong Kong. Studies for Beijing [1,34,54] have also found that air quality conditions over remote rural areas are much better than at urban and suburban sites, as well as having different temporal variations in $PM_{2.5}$ concentration between urban and rural areas. However, the findings of the present study differ from Zhao et al.'s findings in Beijing [34] in that the four-year mean $PM_{2.5}$ concentrations over a remote rural site in Hong Kong (Tap Mun) are comparable with the four-year mean $PM_{2.5}$ concentrations observed over the urban/suburban sites. One-way ANOVA testing shows statistically significant differences in mean values between the air quality monitoring stations (Table 3). For example, in spring, the mean $PM_{2.5}$ concentration for Central air quality monitoring station is statistically different from the other stations, whereas, no significant difference was observed between the mean values for Tsuen Wan and Yuen Long, and between Tung Chung and Tap Mun. Similarly, for winter, no statistical differences were observed in mean values for Yuen Long and Tung Chung, which are close to the Pearl River Delta (PRD) region and affected by pollutants transported from there. However, a significant difference in mean values was observed for other stations. The summary of the one-way ANOVA test for other seasons is given in Table 3.

Table 3. Seasonal statistics of $PM_{2.5}$ mass concentrations observed at the air quality monitoring stations in Hong Kong from 2005 to 2008 using the one-way ANOVA test. N corresponds to the number of hourly observations in a season.

Air Quality Monitoring Stations	$PM_{2.5}$ Concentrations μg·m^{-3})			[1] Grouping			
	N	[2] Mean	StDev				
Time Period: Spring (2005–2008)							
Central		45.77	22.24	A			
Tsuen Wan		38.63	21.71		B		
Yuen Long	6800	38.39	22.78		B		
Tung Chung		34.55	24.97			C	
Tap Mun		34.55	20.97			C	
Time Period: Summer (2005–2008)							
Central		31.48	20.06	A			
Tsuen Wan		24.10	18.19		B		
Yuen Long	6781	23.15	18.89			C	
Tap Mun		18.20	18.88				D
Tung Chung		17.92	18.16				D
Time Period: Autumn (2005–2008)							
Yuen Long		51.32	26.87	A			
Central		51.27	26.11	A			
Tung Chung	6863	48.27	28.99		B		
Tsuen Wan		47.39	25.64		B		
Tap Mun		43.37	24.37			C	
Time Period: Winter (2005–2008)							
Yuen Long		54.77	28.04	A			
Tung Chung		54.00	31.76	A			
Central	8698	51.88	24.80		B		
Tsuen Wan		49.79	25.79			C	
Tap Mun		47.48	24.19				D

[1] Grouping information using the Tukey method in one-way ANOVA test; [2] mean values that do not share a letter (A, B, C, and D) are significantly different.

Figure 2 shows a decreasing trend in monthly mean $PM_{2.5}$ concentrations from winter to summer and increasing trend from summer to winter at all stations, irrespective of land cover type and local anthropogenic activities. It has been observed that there are clear seasonal changes due to the overwhelming impacts of regional sources (from the PRD region of Mainland China) in winter and the dominance of local anthropogenic emissions in summer. The similar seasonal pattern in $PM_{2.5}$ concentrations that we observe in this study between urban/suburban and rural areas suggests the dominance of seasonal changes.

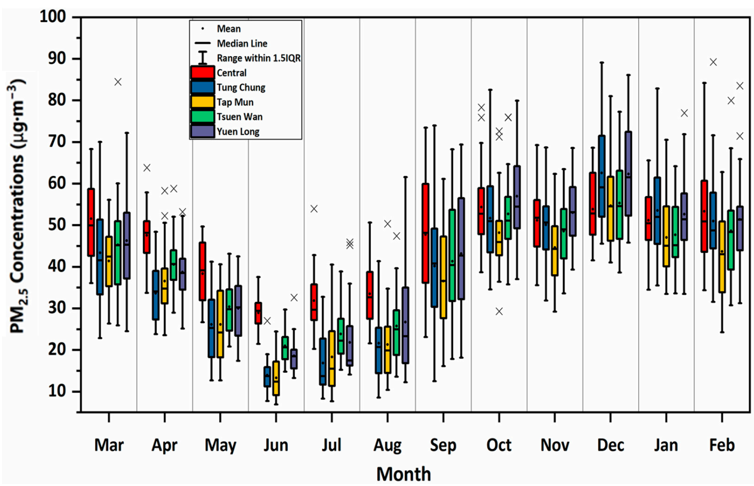

Figure 2. Box plots of the monthly mean of $PM_{2.5}$ concentrations from 2005 to 2008 at five air quality monitoring stations (Central, Tsuen Wan, Tung Chung, Yuen Long, and Tap Mun). Where, '×' represents the outliers.

Results show that the magnitude of variations in monthly mean $PM_{2.5}$ concentrations over the remote rural area (Tap Mun: Yellow box) is the same as over the suburban and residential area (Tung Chung) from March to August. Overall, a decreasing trend in $PM_{2.5}$ concentrations is observed from January to June at all air quality monitoring stations, while an increasing trend is observed from June to December, and these results indicate improved air quality conditions during the month of June. Monthly mean $PM_{2.5}$ concentrations show a unimodal distribution during the study years 2007 and 2008, as was also observed by Gupta et al. [38] for the year 2002 in Hong Kong. The $PM_{2.5}$ concentrations at Central (urban) air quality monitoring station are high during spring and summer compared to the other stations, which may be attributed to high vehicle emissions, as well as other substantial anthropogenic activities. However, during autumn and winter high $PM_{2.5}$ levels are observed at all stations, and significantly higher levels are observed at Tung Chung and Yuen Long in December, probably explained by regional pollutant sources, since they are close to the Chinese Mainland.

In addition to daily and monthly mean temporal variations, the four-year mean $PM_{2.5}$ concentrations were plotted with respect to the station, year, and season (Figure 3). Figure 3a shows that Central is the most polluted area (45.34 $\mu g \cdot m^{-3}$), which may be due to both regional as well as local vehicle emissions, followed by Yuen Long (42.28 $\mu g \cdot m^{-3}$), which is subject to pollution transport from the neighboring PRD region. Tap Mun (36.29 $\mu g \cdot m^{-3}$) is the least polluted site, although it may be affected by regional pollutants, as well as by emissions from ocean-going vessels (OGV). However, overall, the differences were not between the stations, which again suggests regional air pollution impacts Hong Kong's air quality. Figure 3b shows that the highest and lowest $PM_{2.5}$ concentrations were observed in 2005 and 2008, respectively. However, these differences are not significant, suggesting that Hong Kong's air quality conditions did not change during the study period. Figure 3c shows significant differences in the four-year mean $PM_{2.5}$ concentrations; the highest concentrations were observed in winter (52.68 $\mu g \cdot m^{-3}$) and the lowest concentrations were observed in summer (22.46 $\mu g \cdot m^{-3}$). Overall, mean $PM_{2.5}$ concentrations over the four-years, with respect to (i) stations, (ii) year (2005 to 2008), and (iii) seasons (except for summer), were greater than the Hong Kong AQO (35 $\mu g \cdot m^{-3}$) which indicates poor air quality conditions in Hong Kong.

Figure 4 shows the four-year mean $PM_{2.5}$ concentrations plotted against days (weekdays and weekends) with respect to each air quality monitoring station (Figure 4a) and the combined mean value for all stations (Figure 4b). Similar to the previous analyses, significantly higher $PM_{2.5}$ levels were observed at Central air quality monitoring station, probably mainly due to local vehicle emissions in this congested and high-rise urban site. It is notable that concentrations at Tap Mun rural station are lower, from 3 to 9 $\mu g \cdot m^{-3}$, than at other stations but show a similar trend, which must be attributed to regional emission sources, as Tap Mun is a remote rural island in the northeast of Hong Kong, having no local emissions. For all stations combined by week (Figure 4b), minor variations are evident between different days of the week, as $PM_{2.5}$ concentrations varied from 39.14 $\mu g \cdot m^{-3}$ on Wednesdays to 40.3 $\mu g \cdot m^{-3}$ on Fridays, and all days were greater than the Hong Kong AQO (35 $\mu g \cdot m^{-3}$). These results suggest that Hong Kong faces the same high levels of air pollution during both weekdays and weekends.

To investigate hourly pollution patterns in Hong Kong, the four-year mean $PM_{2.5}$ concentrations were filtered by hours between 00:00 and 23:00. Figure 5a shows the bimodal distribution for $PM_{2.5}$ concentrations for all stations except Tap Mun, where a unimodal distribution was observed. Two peaks were observed during office hour times; i.e., the first peak was at 08:00 and the second peak at 18:00, and those peaks are most prominent at Central air quality monitoring station. These peaks also indicate the contribution of local pollutants to Hong Kong's air quality conditions. Only a single peak was observed (at 10:00) at Tap Mun air quality station, as Tap Mun does not have local automobile pollution. Figure 5b shows an overall pattern of $PM_{2.5}$ concentrations in Hong Kong for each hour. The highest and lowest PM2.5 concentrations were observed at 18:00 (44.83 $\mu g \cdot m^{-3}$) and 08:00 (33.09 $\mu g \cdot m^{-3}$), respectively. Figure 5 shows that only for the hours 02:00, 03:00, and 04:00, were PM2.5 concentrations less than the Hong Kong AQO (35 $\mu g \cdot m^{-3}$), whereas the concentrations for other hours were greater than the Hong Kong AQO.

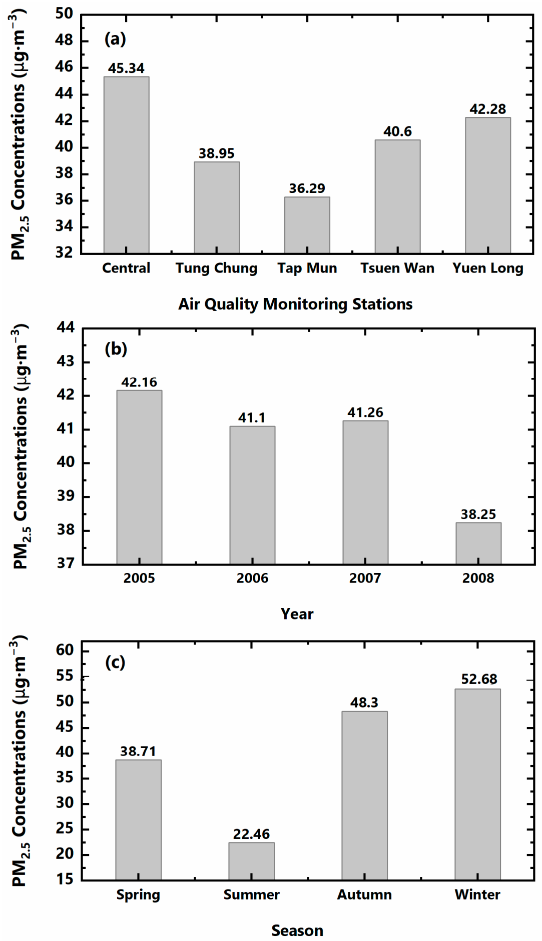

Figure 3. Four-year (2005–2008) mean $PM_{2.5}$ concentrations with respect to (**a**) air quality monitoring stations, (**b**) year, and (**c**) season.

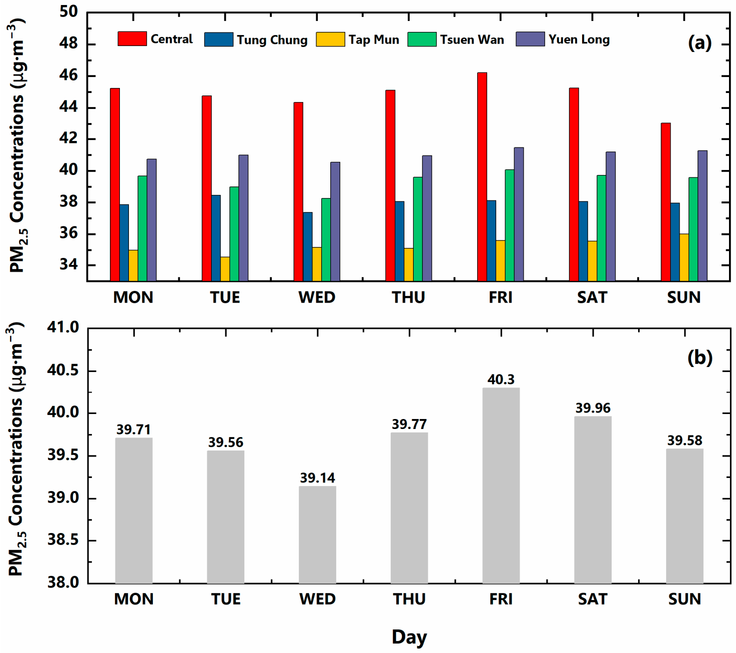

Figure 4. Four-year (2005–2008) mean $PM_{2.5}$ concentrations for weekdays and weekends with respect to air quality monitoring stations (**a**) and when all the stations combined together (**b**).

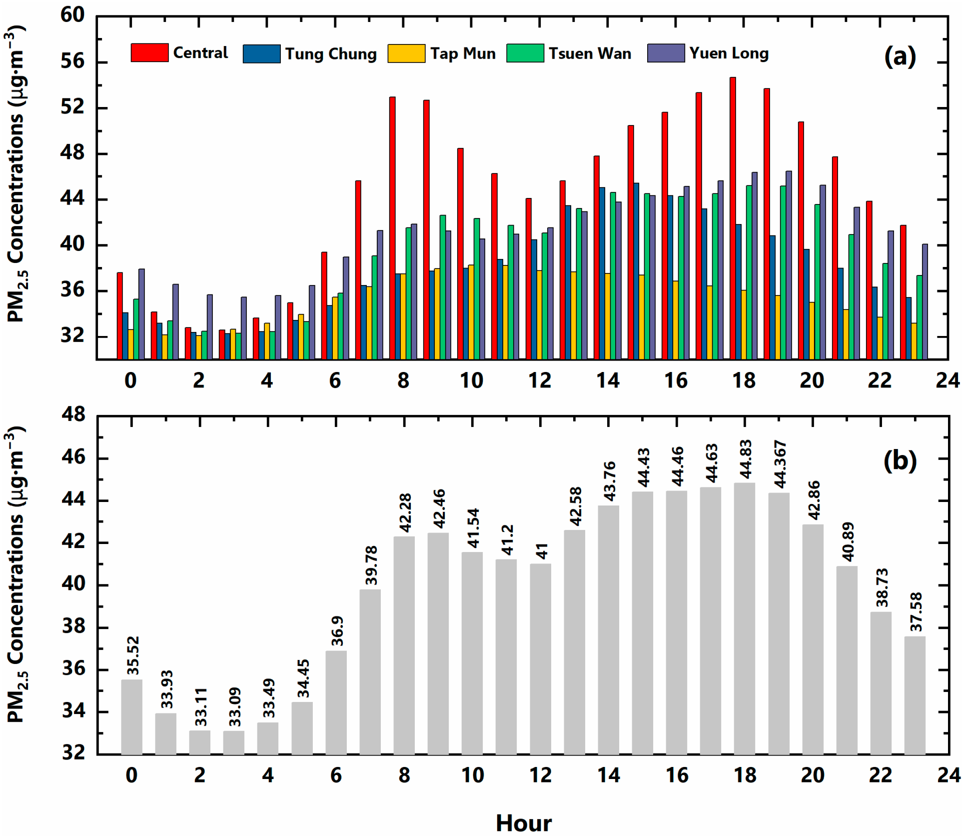

Figure 5. Four-years (2005–2008) of mean $PM_{2.5}$ concentrations for daily hours with respect to air quality monitoring stations (**a**) and when all the stations are combined (**b**).

Relationship with Meteorological Parameters

For a better understanding of PM2.5 variability, the relationships between PM2.5 and meteorological parameters, such as TEMP, RH, WS, and WD were analyzed at Central, Tsuen Wan, Tung Chung, Yuen Long, and Tap Mun air quality monitoring stations from March 2007 to February 2009 (hereafter from 2007 to 2008). The meteorological parameters were obtained from the Hong Kong Observatory, and RH data were not available at the remote rural Tap Mun station during the study period. Therefore, the relationship between PM2.5 and meteorological parameters were established at Tap Mun area without using RH data.

The daily mean TEMP, RH, WS, and WD were found to be negatively correlated with daily mean PM2.5 concentrations for all air quality monitoring stations when the four seasons are combined together (Table 4). Positive values of the Pearson's correlations are observed for individual seasons particularly during the summer, autumn and winter seasons for some variables, such as TEMP and WD. The relationship between PM2.5 concentrations and all the meteorological parameters are established using the multiple linear regression (MLR) statistical methods by combining all the seasonal data, and results show good agreement between them, with correlation coefficients (r) of 0.67 (Yuen Long), 0.65 (Tung Chung), 0.56 (Tsuen Wan), 0.54 (Central), and 0.54 (Tap Mun) observed at respective air quality monitoring stations. These results suggest that some parameters, which could be expected to explain more variations in $PM_{2.5}$, such as aerosol optical properties, are required, in order to improve the $PM_{2.5}$ estimation. Interestingly, the values of r significantly increased when regression analysis was applied only to the spring and summer data. For example, the meteorological parameters can explain 80% of the variability in daily mean $PM_{2.5}$ concentrations at Yuen Long (Equation (1)), 77% at Tung Chung (Equation (2)), 72% at Central (Equation (3)), 71% at Tsuen Wan (Equation (4)), and 67% at Tap Mun (Equation (5)), and achieve an overall variability of 70% when data from all the stations are combined (Equation (6)). However, in autumn and winter, the meteorological parameters can explain only 50% of the variability in $PM_{2.5}$ concentrations at Yuen Long, 40% at Tung Chung, 39% at Central, 35% at Tsuen Wan, and 21% at Tap Mun air quality monitoring stations (equations for autumns and winters are not given here due to weak correlations compared to spring and summer). The results show a weak correlation between PM2.5 concentrations and meteorological parameters during the winter season in Hong Kong, which is caused by the overwhelming regional impact of long-distance transport from the PRD, on a large spatial scale. This is different for studies reported for Kolkata, India [44], and for Hanoi, Vietnam [39] during the winter season. These findings suggest that the relationship between $PM_{2.5}$ and meteorological parameters can vary from region to region due to local prevailing meteorological conditions. The above findings are reasonable, as the meteorological parameters used for regression analysis actually reflect the weather conditions and atmospheric stability when the $PM_{2.5}$ monitoring was done, both of which are critical influential factors of the spatial distribution of aerosols. Moreover, the seasonal variations of the local weather system of Hong Kong and its impact on $PM_{2.5}$ are well reflected by the regression models because the temporal patterns in the meteorological parameters were introduced. This also provides useful knowledge on how to properly adopt meteorological data as an information source for local air quality investigations. In summary, it can be concluded from the analyses that TEMP, RH, WS, and WD are practically useful indicators of variations in $PM_{2.5}$ concentrations over urban, suburban, and rural areas of Hong Kong for spring and summer but are inappropriate for autumn and winter.

$$\begin{gathered}[PM_{2.5}] = 198 - 2.30\,[TEMP] - 1.08\,[RH] - 10.9\,[WS] \\ [Station:\ Yuen\ Long\ (urban),\ r\ =\ 0.80,\ Time\ period\ =\ 2007\text{–}2008\ (spring\ and\ summer)]\end{gathered} \tag{1}$$

$$\begin{gathered}[PM_{2.5}] = 183 - 2.92\,[TEMP] - 0.89\,[RH] - 3.27\,[WS] \\ [Station:\ Tung\ Chung\ (suburban),\ \mathrm{r}\ =\ 0.77,\ Time\ period\ =\ 2007\text{–}2008\ (spring\ and\ summer)]\end{gathered} \tag{2}$$

$$\begin{gathered}[PM_{2.5}] = 163 - 2.37\,[TEMP] - 0.76\,[RH] -\ 2.46\,[WS] \\ [Station:\ Central\ (urban),\ r\ =\ 0.72,\ Time\ period\ =\ 2007\text{–}2008\ (spring\ and\ summer)]\end{gathered} \tag{3}$$

$$\begin{gathered}[PM_{2.5}] = 123 - 1.73\,[TEMP] - 0.60\,[RH] - 0.80\,[WS] \\ [Station:\ Tsuen\ Wan\ (urban),\ r\ =\ 0.71,\ Time\ period\ =\ 2007\text{–}2008\ (spring\ and\ summer)]\end{gathered} \tag{4}$$

$$\begin{gathered}[PM_{2.5}] = 95.2 - 2.63\,[TEMP] - 1.22\,[WS] \\ [Station:\ Tap\ Mun\ (rural),\ r\ =\ 0.67,\ Time\ period\ =\ 2007\text{–}2008\ (spring\ and\ summer)]\end{gathered} \tag{5}$$

$$\begin{gathered}[PM_{2.5}] = 151 - 2.36[TEMP] - 0.68\,[RH] - 2.06\,[WS] \\ [Station:\ all\ (five),\ r\ =\ 0.70,\ Time\ period\ =\ 2007\text{–}2008\ (spring\ and\ summer)]\end{gathered} \tag{6}$$

A previous study conducted during 1983–1992 [55] showed that higher values of air pollution in Hong Kong were associated with surface WD between 225° and 30°, which were attributed to power stations, industry, and motor vehicles. In the current study, hourly $PM_{2.5}$ concentrations plotted as against hourly WD (Figure 6) showed similar results in terms of the influence of wind direction. Figure 5 shows that only 32.76% (WD between 230–40°) of air masses were arriving from the PRD region, while 67.24% were arriving from the open ocean (WD between 45–225°). However, due to the Coriolis effect on the long-distance trajectory, many of the winds of the ocean originated on the mainland. These results suggest that the air quality of Hong Kong was influenced by air masses arriving from PRD and the Chinese mainland, although approaching Hong Kong from the ocean side. In recent years, ocean-going vessels (OGV) have become the biggest source of air pollution in Hong Kong; therefore, air masses arriving from the ocean may also be affected by OGV emissions. To further investigate the $PM_{2.5}$ contribution to Hong Kong's air quality, $PM_{2.5}$ was divided into three different groups; i.e., $PM_{2.5} \leq 35$, $35 < PM_{2.5} \leq 75$, and $PM_{2.5} > 75$, for the both WDs (45–225°and 230–40°) (Table 5). For $PM_{2.5} \leq 35$ and $35 < PM_{2.5} \leq 75$, more measurements were available for air masses arriving from the ocean side, and for $PM_{2.5} > 75$ more measurements were available for air masses arriving from the land. These results suggest that air masses arriving from both the land and ocean influence the poor air quality conditions in Hong Kong.

Table 4. Pearson's correlation between daily mean $PM_{2.5}$ and meteorological parameters for the years 2007 and 2008. Bold text represents statistically more significant correlations for *p*-values < 0.005.

[1] AQMS	Time Period	Meteorological Parameters							
		TEMP		RH		WD		WS	
		[2] r	[3] P	r	P	r	P	r	P
Central	Spring	−0.26	0.011	**−0.35**	**0.001**	−0.16	0.117	−0.03	0.810
	Summer	0.25	0.018	−0.22	0.037	−0.04	0.709	−0.01	0.894
	Autumn	0.10	0.366	−0.26	0.012	**0.32**	**0.002**	**−0.40**	**0.000**
	Winter	**0.33**	**0.001**	**−0.30**	**0.004**	0.01	0.898	−0.16	0.120
	2007–2008	**−0.35**	**0.000**	**−0.45**	**0.000**	**−0.30**	**0.000**	−0.06	0.274
Tsuen Wan	Spring	−0.20	0.058	**−0.61**	**0.000**	−0.29	0.005	**−0.32**	**0.002**
	Summer	**0.36**	**0.000**	−0.23	0.030	0.18	0.080	−0.12	0.251
	Autumn	−0.05	0.655	−0.13	0.236	0.07	0.493	−0.18	0.091
	Winter	0.17	0.107	**−0.33**	**0.001**	−0.09	0.399	**−0.37**	**0.000**
	2007–2008	**−0.42**	**0.000**	**−0.47**	**0.000**	**−0.40**	**0.000**	−0.13	0.012
Tung Chung	Spring	**−0.42**	**0.000**	**−0.33**	**0.001**	−0.22	0.039	**−0.34**	**0.001**
	Summer	**0.32**	**0.002**	−0.27	0.009	0.06	0.581	−0.14	0.185
	Autumn	−0.12	0.242	−0.18	0.086	0.01	0.921	−0.19	0.065
	Winter	0.24	0.021	**−0.41**	**0.000**	0.19	0.077	−0.29	0.006
	2007–2008	**−0.50**	**0.000**	**−0.49**	**0.000**	**−0.36**	**0.000**	**−0.30**	**0.000**
Yuen Long	Spring	**−0.36**	**0.000**	**−0.40**	**0.000**	−0.04	0.676	**−0.33**	**0.001**
	Summer	**0.31**	**0.002**	−0.29	0.005	0.09	0.395	**−0.36**	**0.000**
	Autumn	−0.06	0.565	−0.29	0.006	0.19	0.073	−0.15	0.168
	Winter	0.28	0.008	**−0.35**	**0.001**	0.01	0.909	−0.26	0.013
	2007–2008	**−0.43**	**0.000**	**−0.56**	**0.000**	**−0.24**	**0.000**	**−0.17**	**0.001**
Tap Mun	Spring	**−0.38**	**0.00**	-	-	0.07	0.512	0.00	1.00
	Summer	0.25	0.032	-	-	0.19	0.094	−0.06	0.599
	Autumn	−0.30	0.010	-	-	0.30	0.012	0.26	0.31
	Winter	0.30	0.010	-	-	0.09	0.448	−0.08	0.500
	2007–2008	**−0.53**	**0.000**	-	-	**0.32**	**0.000**	**0.33**	**0.000**

[1] AQMS = Air Quality Monitoring Stations; [2] r = Pearson's correlation; [3] P = *p*-value.

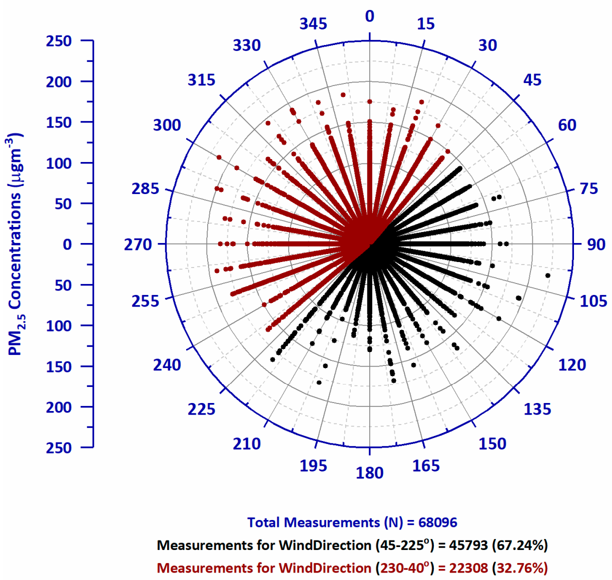

Figure 6. Hourly $PM_{2.5}$ concentrations from all air quality monitoring stations including Central, Tap Mun, Tsuen Wan, Yuen Long, and Tung Chung as a function of corresponding hourly surface wind direction in Hong Kong (2007–2008).

Table 5. Statistics of hourly $PM_{2.5}$ concentrations from all air quality monitoring stations, including Central, Tap Mun, Tsuen Wan, Yuen Long, and Tung Chung, as a function of corresponding hourly surface wind direction in Hong Kong (2007–2008).

Wind Direction	$PM_{2.5}$ Concentrations					
	$PM_{2.5} \leq 35$		$35 < PM_{2.5} \leq 75$		$PM_{2.5} > 75$	
	N	Mean	N	Mean	N	Mean
45–225°	25943	20.50	17160	50.95	2690	92.47
230–40°	9195	21.75	9668	52.50	3445	97.90

5. Conclusions

The prime objective of this study was to investigate the characteristics of fine particulate matter ($PM_{2.5}$) with respect to meteorological parameters over urban, suburban, and rural areas of Hong Kong. For this purpose, $PM_{2.5}$ data and meteorological parameters were obtained from the air quality monitoring stations and Hong Kong Observatory, respectively. The results showed a similar pattern of temporal variations in $PM_{2.5}$ concentrations over urban, suburban, and rural areas of Hong Kong, which suggest a significant contribution of regional aerosol emissions in Hong Kong's air quality, and which are dominant in the winter season [56]. The temporal analyses showed poor air quality conditions during winter and good air quality conditions during summer. In spring and summer, $PM_{2.5}$ concentrations were significantly higher over the Central (city area, commercial area, and urban populated area) air quality station compared to the other stations, which are probably caused by local vehicle emissions. However, in autumn and winter, higher levels of $PM_{2.5}$ concentrations were observed over both the Tung Chung suburban and residential area, and the Yuen Long urban and residential area, which is likely due to the contribution of regional pollutants, since these stations are close to the Chinese Mainland. It was also found that air masses arriving from the ocean, also affect Hong Kong's air quality. These results suggest that the long-distance transport of air pollutants from the PRD region, as well as emissions from the OGV, have a great influence on Hong Kong's air quality. This must be addressed by regional-scale collaboration on air quality management. Results also showed that meteorological parameters are good indicators of variations in $PM_{2.5}$ concentrations, and can be used for the prediction of $PM_{2.5}$ concentrations, especially during spring and summer.

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